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GAS CAVITY REACTOR SIMULATION EXPERIMENT

by
G. D. Pincock
J. F. Kunze

Prepared for
NATIONAL AERONAUTICS and SPACE ADMINISTRATION
CONTRACT NAS 3-6104

NUCLEAR MATERIALS and PROPULSION OPERATION
ATOMIC PRODUCTS DIVISION
GENERAL ELECTRIC
Cincinnati 15, Ohio

NOTICE

FINAL REPORT

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GENERAL ELECTRIC COMPANY
NUCLEAR MATERIALS AND PROPULSION OPERATION

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ABSTRACT

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This report contains the critical experiment test results from measurements performed in the center of the NASA Tungsten reactor to simulate a gaseous fueled cavity reactor. Gaseous UF_6 fuel was simulated with the same amount of solid sheet fuel distributed over the same volume and the reactivity difference between the two types of fuel was measured. It was found that the sheet fuel was worth about 6% less than the gaseous UF_6 fuel.

Author

1.0 INTRODUCTION

An experiment was conducted in the NASA Tungsten reactor as requested by the NASA-Lewis Research Center to determine if enriched UF_6 fuel in the gaseous form could be simulated with one mil thick sheet uranium fuel. In order to accomplish the experiment, the center seven tungsten fuel cartridges and fuel tubes were removed and an insert assembly was inserted in their place. This report contains the results of the measurements performed during this test series. The work was performed in Idaho at the Low Power Test Facility and was covered by contract number NAS 3-6104.

2.0 DESCRIPTION OF REACTOR AND INSERT

The tungsten reactor, before modification, consisted of 37 fuel tubes set on a 3.1 inch pitch. The fuel cartridges were wrapped to simulate the desired tungsten, enriched uranium concentration for the proposed tungsten clad fuel cartridges. The reactor was water moderated and beryllium reflected. A detailed description of the reactor and fuel cartridge loading is given in the data report for the tungsten reactor.[1] One modification was made to the tungsten fuel cartridges. All of the stainless steel cylinders (cylinder 4) with three mils of tungsten were removed. This was required to obtain a critical assembly.

The insert consisted of an outer aluminum tank with an outside diameter of 8.0 inches and a wall thickness of .125 inch. Inside this tank was another aluminum tank which was 7.0 inches O.D. with a .064-inch wall thickness. These two tanks formed a 1/2-inch annular void which was evacuated to provide a thermal shield between the water moderator in the "parent core" and the insert water. This is illustrated in Figure 1. In the very center of the reactor was placed the aluminum tank containing the fuel. Two center tanks, 27.5 inches long, were made, one contained the sheet fuel and the other contained UF_6. The tanks were identical, being 5 inches in diameter (o.d.) with a .125-inch wall thickness. The tank into which sheet was placed had a removable cap at the top to allow loading the tank with fuel. It also had a 1/4-inch diameter aluminum tube connected at the top and bottom of the tank to permit filling the tank with argon while it was in the reactor to prevent oxidation of the fuel when heated to temperatures near $190^{o}F$. Both tanks were water tight to prevent water from entering them and, of course, the UF_6 tank was seal welded to prevent escape of the gaseous material.

(1) G. D. Pincock, M. A. Jacoby, GE-NMPO, NASA CR-54453, July 21, 1965, pp. 8 to 11.

CAVITY INSERT
NASA REACTOR LAYOUT
TOP VIEW - LOOKING DOWN

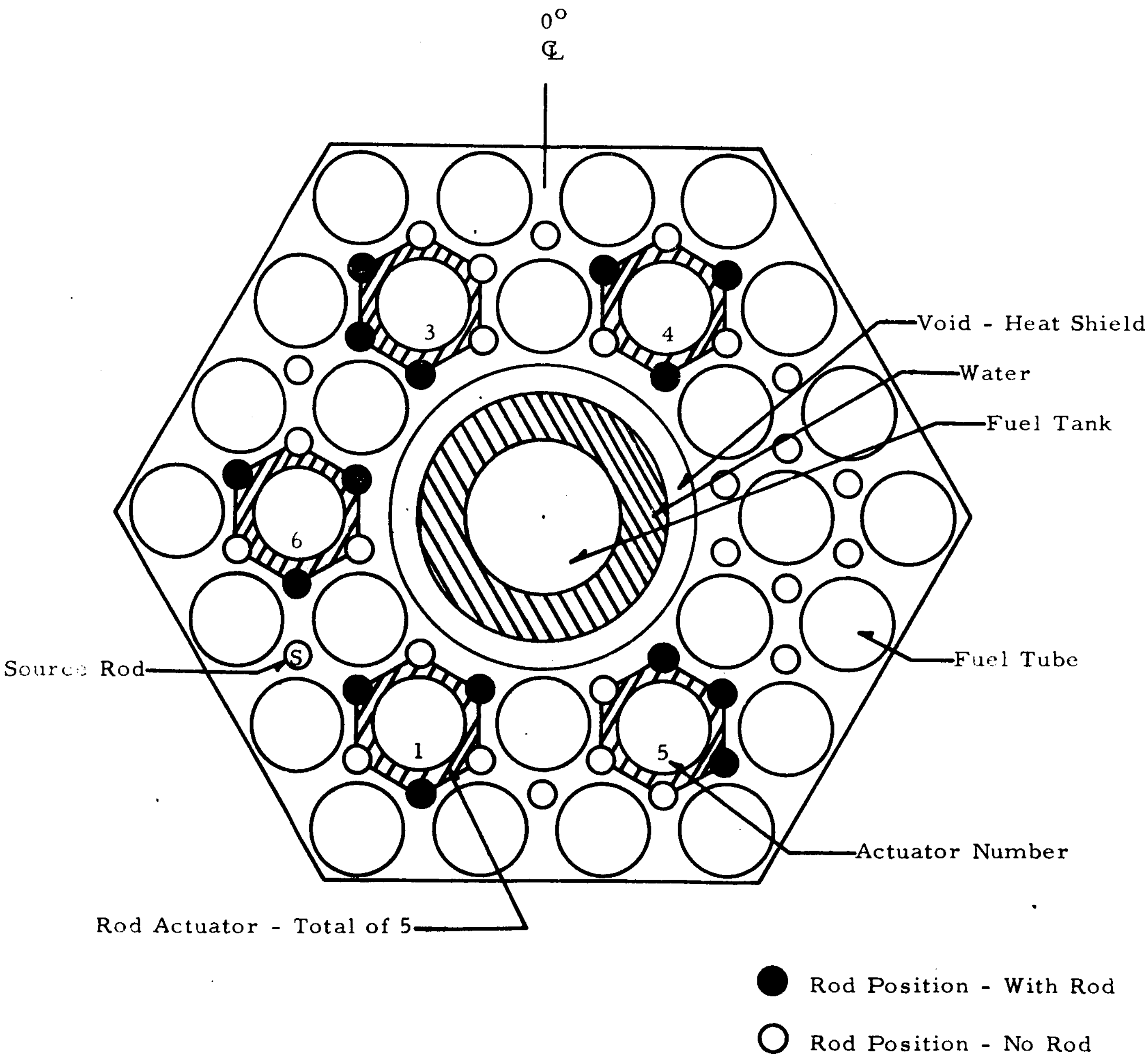


Figure 1

The water around the center tank was heated to near boiling and in turn heated the tank containing fuel. This was necessary in order to vaporize the UF_6. The water was heated exterior to the reactor and was then circulated through the insert. The evacuated air gap which served as a heat shield was necessary to prevent transfer of heat from the insert to the "parent core" moderator. The water in the "parent core" was normally around 70^{o}F whereas the insert was normally operated near 190^{o}F.

Beryllium reflectors were placed on both ends of the insert to reduce end leakage of neutrons. These reflectors were assembled from beryllium pieces available in Idaho. The layout of the reflectors is shown in Figure 2.

The sheet fuel was placed in the insert tank on aluminum screens. The concentration of fuel had to be kept to around 200 grams so that the same amount of fuel could be vaporized in the form of UF_6 below the boiling point of water at the existing barometric pressure. The aluminum screens were cut and shaped to form a corrugated pattern as shown in Figure 3. Each screen held seven one mil thick sheets of fuel 2.875 inches long by 1.437 inches wide. It was necessary to trim a small amount of fuel off of the edge of four of the sheets which were next to the tank wall. A total of 22 screens and 154 sheets of fuel were used to fill this tank.

The fuel was carefully cleaned and weighed before the experiment started. The total weight was 171.57 grams of 93.2% enriched uranium. The specifications on the material placed in the other tank gave 254.69 grams of UF_6. Of this, .6736 was 93.23% enriched uranium. This gives 171.56 grams of uranium in the UF_6 tank. In each case, therefore, the same amount of uranium was used.

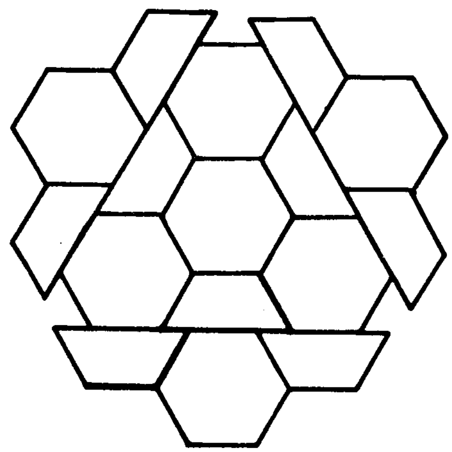
Two sets of aluminum screens were used in the sheet fuel tank to support the fuel. The first set weighed 127.73 grams and the second set added during the test weighed 128.45 grams.

Two thermocouples were placed in the insert water. One was located near the bottom of the tank and the other near the top. Ten other thermocouples were located in the "parent core" moderator. All of the thermocouples were monitored remotely in the control room with a precision millivolt box.

Only five actuators and 15 control rods were used in the reactor for control as shown in Figure 1. Actuator 2 was removed to accommodate the water and gas lines into the insert. The rods on actuators 3 and 5 were placed on one side of the actuator to allow the water drain lines to pass between the fuel tubes.

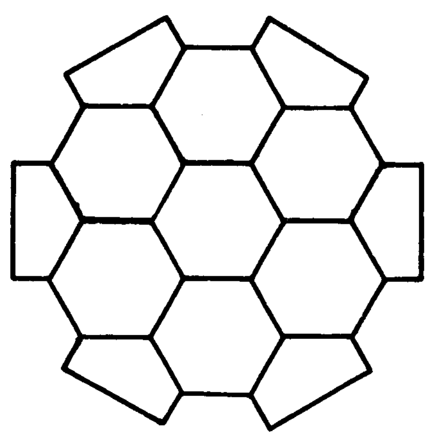
CAVITY INSERT
BERYLLIUM END REFLECTORS

TOP REFLECTOR



4 Inches in Length

BOTTOM REFLECTOR



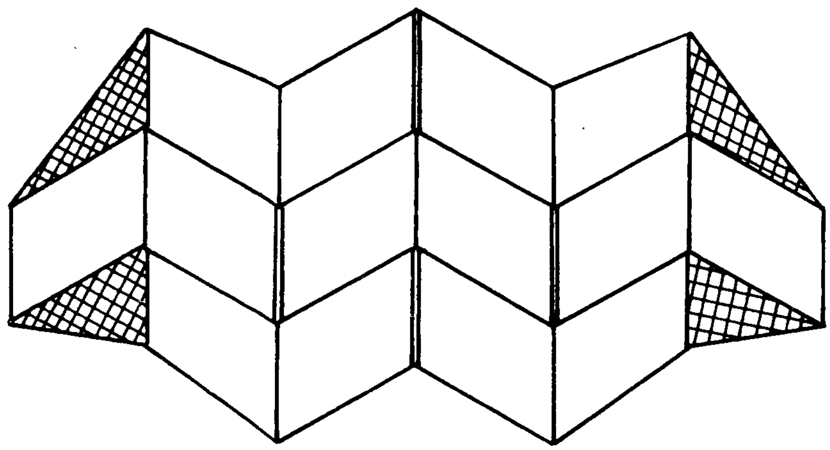
16 Inches in Length

Note: Each hex Be bar is 1.662 ± .005 inches across flats. Those pieces which are not a complete hex are hex bars cut in half.

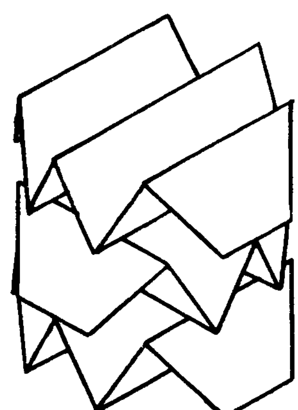
Figure 2

FUEL CARTRIDGE - ALUMINIUM SCREEN

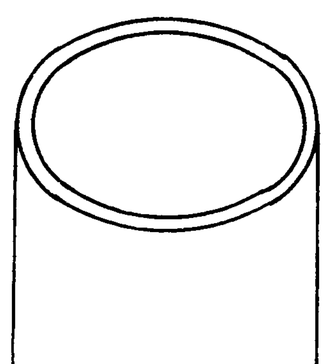
AND SHEET FUEL ARRANGEMENT



Aluminium screen with fuel.



Aluminium screens - 22 required.



Aluminium fuel tube.

Figure 3

3.0 TEST PROCEDURES

As stated in the previous section of this report, 15 control rods were used in the reactor during this test series. The normal procedure was to move all of these rods to the same equally withdrawn position to determine k-excess or changes in k-excess. In order to evaluate the total worth of the rods, they were pulled or "bumped" a small increment. From the resulting period and a valid rod worth curve, the total worth of the rods was readily determined. Knowing total rod worth and the percent of this worth inserted in the reactor, the system excess reactivity was calculated. This procedure, of course, required the use of a representative rod worth curve. Prior to modifying the tungsten reactor for this test, measurements were made to determine the rod worth curve using 18 rods in the reactor. All 18 rods were moved as a unit. Since the total worth of 15 rods in this assembly was expected to be only slightly less than the total worth of 18 rods in the unmodified tungsten reactor, the measurement of a new rod worth curve was considered to be unnecessary unless results showed otherwise. This curve is presented in both graphical and tabular form in Figure 4 and Table 1. The procedures followed in determining total rod worth and excess reactivity from rod "bumps" and the rod worth curve are described in more detail in a previous NASA data report.(2)

The exposure of catcher foils in the insert to determine the epicadmium fission fraction was accomplished by using standard catcher foil techniques. The aluminum catcher foils were exposed against enriched uranium fuel for a period of 20 minutes. The cadmium covered catcher foils were covered with 20 mils of cadmium. Each catcher foil was counted after exposure in the reactor on the semi-automatic counting system at the LPT facility. Normalizer catcher foils were also exposed at the same time the other catcher foils were in the reactor. The purpose of these normalizer foils and the exact counting procedures are described in detail in one of the earlier reports covering a NASA experiment performed by the General Electric Company.(3)

(2). Ibid, p. 13

(3) G. D. Pincock, M. A. Jacoby, "Data Results From NASA Fuel Cartridge Experiment in 630A Critical Experiment Reactor", GE-NMPO, GEMP-262, Dec. 23, 1963, pp. 18 to 24.

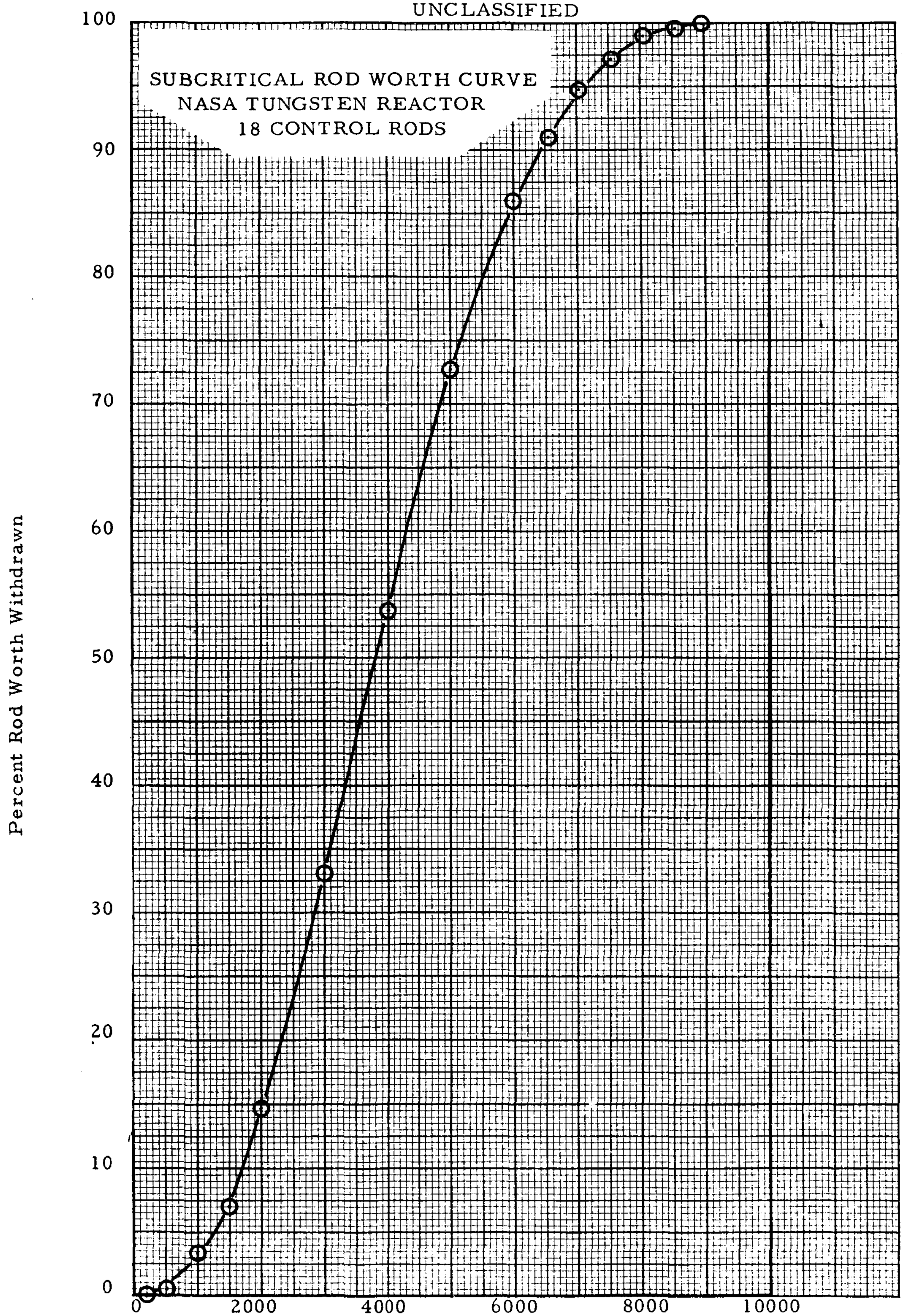


Figure 4 Ratiometer Reading

TABLE 1

SUBCRITICAL ROD WORTH CURVE

NASA CORE CONFIGURATION

Source in Center of Reactor
Percent Rod Worth Inserted

Ratiometer Reading

	0	100	200	300	400	500	600	700	800	900
0	100.00	100.00	99.92	99.76	99.53	99.22	98.84	98.38	97.84	97.22
1000	96.53	95.75	94.89	93.95	92.93	91.83	90.65	89.38	88.02	86.57
2000	85.03	83.43	81.76	80.04	78.27	76.45	74.59	72.69	70.76	68.80
3000	66.81	64.79	62.75	60.70	58.64	56.57	54.50	52.43	50.36	48.29
4000	46.23	44.19	42.17	40.17	38.20	36.26	34.37	32.52	30.72	28.98
5000	27.30	25.69	24.14	22.64	21.20	19.81	18.48	17.20	15.98	14.81
6000	13.69	12.62	11.60	10.63	9.71	8.84	8.02	7.25	6.52	5.84
7000	5.20	4.60	4.05	3.54	3.07	2.64	2.25	1.90	1.58	1.29
8000	1.03	.82	.62	.45	.31	.19	.10	.03	0	0

DIFFERENCE TABLE

	0	100	200	300	400	500	600	700	800	900
0	0	0	.08	.16	.23	.31	.38	.46	.54	.62
1000	.69	.78	.86	.94	1.02	1.10	1.18	1.27	1.36	1.45
2000	1.54	1.60	1.67	1.72	1.77	1.82	1.86	1.90	1.93	1.96
3000	1.99	2.02	2.04	2.05	2.06	2.07	2.07	2.07	2.07	2.07
4000	2.06	2.04	2.02	2.00	1.97	1.94	1.89	1.85	1.80	1.74
5000	1.68	1.61	1.55	1.50	1.44	1.39	1.33	1.28	1.22	1.17
6000	1.12	1.07	1.02	.97	.92	.87	.82	.77	.73	.68
7000	.64	.60	.55	.51	.47	.43	.39	.35	.32	.29
8000	.26	.21	.20	.17	.14	.12	.09	.07	.04	.02

4.0 MEASUREMENT OF EPICADMIUM FISSION FRACTION

The test required that a measurement be made on the surface of center fuel tank to determine the epicadmium fission fraction. It was further required that this fraction be less than .25. The measurement was accomplished by placing four bare and four cadmium covered catcher foils on the inner surface of the tank containing sheet fuel. The foils were placed at the vertical midplane of the reactor. All eight foils were 1/4 inch in diameter and were exposed on a single run. The resulting normalized counts are given in Table 2. It will be noted here that the epicadmium fission fraction was .0453 ± .0011.

TABLE 2

EPICADMIUM FISSION FRACTION

Foil No.	Angle*	Type Foil		Normalized Counts **
1	0	Cd Covered		3478
2	90	↓		3511
3	180	↓		3478
4	270	↓		3555
			Avg.	3506 ± 36
5	30	Bare		79621
6	120	↓		77455
7	210	↓		75433
8	300	↓		76879
			Avg.	77447 ± 1756

$$\text{Epicadmium Fission Fraction} = \frac{3506 \pm 36}{77447 \pm 1756} = .0453 \pm .0011$$

* Degrees from core centerline (clockwise looking down).

** Decay corrector set at 102110 counts - Normalizers counted 114534 counts per minute at 50 minutes after shutdown.

5.0 ROD WORTH AND EXCESS REACTIVITY MEASUREMENTS

The main purpose of this test was, of course, to determine if gaseous UF_6 could be simulated with solid sheet fuel. The reactivity measurements were, therefore, oriented towards this end. With the sheet fuel tank in the reactor, measurements were made to determine the worth of the fuel, the worth of the aluminum screens and the reactivity effect of temperature in the insert water and fuel tank. After completing these measurements, the tank containing UF_6 was placed in the reactor and the change in excess reactivity of the reactor was measured compared to the tank containing sheet fuel. The results of each excess reactivity measurement with the control rods equally inserted into the reactor are presented in Table 3. The average rod worth based on all 14 measurements was 8.275 ± .265% Δ k/k. It will be noted that there are small variations in "parent core" moderator temperature and, after the insert was heated to operating temperature, there were also some small variations in the insert temperature. Because of these changes, it was necessary to make small corrections to the excess reactivity values before determining the reactivity changes due to the different conditions in the insert.

The moderator temperature coefficient of reactivity for the tungsten reactor was previsouly measured to be .0057% Δk/k per ^{o}F change in water temperature. This is a positive coefficient. The effect of temperature increase in the insert only from about 74^{o}F to 193^{o}F was measured to be a positive .0025 ± .0018% Δk/k per ^{o}F change in water temperature.

The data given in Table 3 were re-evaluated using the average rod worth and correcting to a temperature base of 74^{o}F in the parent core moderator and 193^{o}F in the insert (except where noted) using the above moderator temperature coefficients. The results are summarized as follows:

Insert Condition	k-excess % Δ k/k
Al tank but no sheet fuel or Al screen in insert (cold)	1.848 ± .057*
Normal sheet fuel and Al screen in insert (cold)	4.578 ± .146*
" " " " " " " " (hot)	4.874 ± .156
Sheet fuel only removed from insert (hot)	2.325 ± .075
Normal sheet fuel with double Al screen in insert (hot)	4.872 ± .156
UF_6 tank in insert (hot)	5.016 ± .161

* These two values are with the insert at the same temperature as the parent core moderator so both temperatures were corrected to 74^{o}F.

TABLE 3

ROD WORTH AND REACTIVITY MEASUREMENTS

Run No.	Ratiometer Critical	Ratiometer Period	Percent Rod Worth Inserted Critical	Percent Rod Worth Inserted Period	Δ Worth	Period	Total Rod Worth	K_{ex}	Temp. (reactor)	Temp. (insert)	Remarks
1245	5372	5522	.2160	.1952	.0208	.1808	8.692	1.877	66.5	66.5	No Fuel or Screen in Insert
1246	3575	3652	.5502	.5342	.0160	.1358	8.488	4.670	71.0	71.0	Fuel in Insert
1247	3392	3472	.5880	.5715	.0165	.1370	8.303	4.882	74.3	193.6	" " "
1247	3385	3465	.5895	.5729	.0166	.1330	8.012	4.723	74.3	192.5	" " "
1247	3382	3463	.5901	.5734	.0167	.1438	8.611	5.081	74.3	193.2	" " "
1248	4951	5054	.2812	.2643	.0169	.1450	8.580	2.413	75.9	192.0	No fuel but Al screens in Insert
1248	4946	5046	.2821	.2656	.0165	.1368	8.291	2.339	75.7	192.1	" " "
1248	4941	5042	.2829	.2662	.0167	.1382	8.275	2.341	75.6	192.2	" " "
1249	3383	3464	.5899	.5732	.0167	.1366	8.180	4.825	76.4	192.6	Double Al screens Plus Fuel
1249	3380	3462	.5905	.5736	.0169	.1373	8.124	4.797	76.3	192.2	" " "
1249	3380	3460	.5905	.5740	.0165	.1348	8.170	4.824	76.2	192.0	" " "
1250	3297	3380	.6076	.5905	.0171	.1437	8.404	5.106	76.9	193.3	UF_6 in Insert
1250	3293	3380	.6084	.5905	.0179	.1423	7.950	4.837	76.9	193.4	" " "
1250	3291	3380	.6088	.5905	.0183	.1422	7.770	4.730	77.0	193.2	" " "
						Avg.	8.275 ± .265				

Taking the differences in the above values give the following:

Worth of sheet fuel and Al screen (cold)	2.729 ± 157% $\Delta k/k$
Worth of increasing insert temperature from 74.0 to 193.0°F	.296 ± .214% $\Delta k/k$
Worth of fuel only in insert (hot)	2.549 ± .173% $\Delta k/k$
Worth of Al screen in insert (hot)	-.002 ± .221% $\Delta k/k$
Worth of UF_6 over sheet fuel (hot)	.142 ± .224% $\Delta k/k$

As noted here, the UF_6 cartridge was worth more than the sheet fuel cartridge. Based on the worth of the sheet fuel only, the difference was about 6%. It was considered advisable after noting this difference to check again the differences between the two insert cartridges by measuring the difference in a single period. The sheet fuel assembly was placed in the insert and the critical position was established with actuators 4, 5 and 6 fully inserted, actuator 1 withdrawn and actuator 3 at 7652. The UF_6 cartridge was then inserted and the critical position was the same as above except actuator 3 was now at 6569. Actuator 3 was pulled from 6569 to 7652 resulting in a period worth, .151 ± .005% $\Delta k/k$. Between these two measurements the parent core moderator indicated a temperature increase of 0.2 ± 1.0°F and the insert temperature decreased 1.1 ± 1.0°F. Applying these small temperature changes gives a difference between the two cartridges of .152 ± .008% $\Delta k/k$ with the UF_6 still being worth more. Aluminum rods were then placed along the outside of the UF_6 tank to simulate the gas lines on the sheet fuel tank. This caused a slight increase in reactivity of .002 ± .009% $\Delta k/k$. The standard error placed on these values assumes a 1.0°F standard error on temperature and 3% standard error on the period worth.

The reason for the UF_6 being worth more in reactivity was expected to be due to lumping the fuel in the sheet fuel thus causing some self-shielding. To further check this, the center sheet of fuel on each tray was moved to an outer position thus creating a double layer of fuel over a single fuel sheet area on each of the 22 aluminum screens. This double layer of fuel was placed at a different angular position as the screens were inserted back in the tank so that it spiralled around the tank at 90 degree intervals. Lumping the fuel in this fashion decreased k-excess .017 ± .010% $\Delta k/k$. This substantiates the self-shielding effect of the sheet fuel. Appendix A gives further theoretical justification for the difference in reactivity expected between these measurements.

Although there are some reactivity differences between the two types of fuel, these differences are relatively small and can be compensated for by using a little more sheet fuel to account for self-shielding.

6.0 ERROR ANALYSIS

All of the data results contained in this report are presented with a standard error. The catcher foils exposed to determine the epicadmium fission fraction in the insert show a standard error of around 2%. This is based on an assumption that the neutron flux and spectrum is constant around the insert fuel cartridge and that the error is due to normal foil mounting, exposure and counting variations. This standard error is normal for this type of measurement.

The standard error associated with the reactivity measurements are also given. The k-excess values for the different conditions are based on the average control rod worth of 8.275 ± .265% $\Delta k/k$. This gives a standard error of about 3% which is reflected in each of the given k-excess values. This is also a normal error for this type of measurement.

The few measurements discussed in the previous section based on periods or period differences were evaluated on an assumed standard error of 3% for a single period measurement. This value was based on previous experience.

A standard error of $1^{o}F$ was assumed for the water temperatures. This was factored into the data involving differences in periods only since the small uncertainty in temperature was insignificant in the data based on total rod worth and differences in k-excess.

APPENDIX A

Cavity Reactor Mockup

1. Self-shielding of 1-mil U foils, using the formula of Bathe

$$G = \frac{1 - e^{-x}(1 - x) - x^2 E_1(x)}{2^x} = 0.88$$

where $x = \Sigma a$ (foil thickness)

2. FOG calculation showed a power dip through the cavity of 2%, i.e., ratio = 0.98

3. Reactivity effect of a "perturbation" is

$$\Delta\rho = \frac{\Delta n\,(\nu\Sigma_f - \Sigma a)}{n\,\nu\Sigma_f} = \frac{\Delta n}{n}\,\frac{\frac{\nu\Sigma_f}{\Sigma a} - 1}{\frac{\nu\Sigma_f}{\Sigma_a}} = \frac{n - 1}{n}\quad\frac{\Delta n}{n}$$

with $n = 2.06$, $\Delta\rho = \frac{1.06}{2.06}\quad\frac{\Delta n}{n}$

4. If self-shielding difference is $\frac{0.88 - 0.98}{0.93} = -0.108$, then

$$\Delta\rho = -\frac{1.06}{2.06} \times 0.108 = -0.056$$

There should have been a 5.6% difference between the reactivities of the two cavities.

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